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Evaluation of Limit Equilibrium and Finite Element Methods in Slope Stability Analysis - Case Study of Zaremroud Landslide, Iran

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ABSTRACT

The events that result from slope instability that causes a mass of soil to move downward from an earth slope (landslides) are studied in this research. The most important factors of slope instability are the force of gravity and the presence of water, which cause soil erosion at the surface and increase pore pressure at greater depths, thereby reducing soil strength. Iran, with mainly mountainous topography, tectonic activities, high seismicity, and diverse geological and climatic conditions, has the susceptible to landslides. Therefore, the analysis of slope stability and its safety evaluation is crucial in this region. Choosing the right method for sustainability analysis, which is one of the engineers' challenges in estimating the sustainability of a slope, depends on the project conditions and the inherent limitations of each method. This paper presents a case study of the stability analysis of a soil slope using limit equilibrium and finite element methods in Zararmood region in Mazandaran Province of Iran. The results show that the safety factor calculated by the finite element method is about 3% lower than the limit equilibrium method which is negligible due to the simplicity of calculations in the limit equilibrium method.

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1. Introduction

Landslides are the movement of a rock or soil mass on a slope [1] that had become unstable for various reasons. These reasons include earthquake seismic, road constructions, mining activities, eroded river banks etc. Landslides are caused by many factors such as earthquakes, rainfall, and quick melting of snow, as well as factors like topography, rock and soil type, fractures, bed surfaces, and moisture content [2,3]. The main factors of the rock and soil mass motion are gravity, earthquake, road construction, increase in pore water pressure due to the rain, removal of earth from the downstream of the slope and many other factors. The downward movement in the landslide may occur very slowly (only a few millimeters a year) or at a very rapid rate which results in disastrous effects.

Another problem that causes many of the hazards is that most soils are stable for a time period after applying changes such as excavation, but they decrease in stability gradually, which may take several hours, days or even months. This phenomenon has several reasons, such as: 1. Gradual deformation due to the removal of the side barrier or the surrounding soil, which will cause downfall and sliding of soil mass after a while. 2. In clays with high moisture content, soil drying may be associated with contraction cracks, and thus gaps in the soil cause a lack of stability. In particular, the subsequent filling of these gaps with waters can increase the risk of landslide. 3. In dry clay, the next increase in moisture may cause soil loss and collapse.

Landslide in Iran, as a natural disaster, causes a lot of human and financial losses to the country annually. Earth's drift can even occur on the seabed and underwater and be causing tidal waves to result in damages in coastal areas. A large number of landslides resulting from earthquake have been created due to the liquefaction phenomenon. However, another significant number of them were due to the slope failure that, in the static conditions, they also had weak stability. If, for other natural disasters, we assume to have a chance to occur in long periods of time, the potential for the occurrence of the landslide in Iran should be considered at any moment. According to an initial estimate, Five hundred thousand US dollars per year are imposed on the country through landslides, provided that the loss of natural resources is not counted non-returnable [4]. This phenomenon causes economic damage to installations, developmental projects, natural resources, farms, and residential areas every year in most parts of the country, or threatens them. Distributed map of landslides of Iran in 2004 was prepared by the water resources management Department of the Iranian government and accessible on the website of Earth Sciences data [5]. This map, presented in Fig. 1, shows that most of the landslides in Iran occurred at altitudes, especially in the Alborz and Zagros mountains, and most of the large landslides with human casualties are within the Alborz mountains.

Iran is very diverse in terms of natural effects, especially topography. Tectonically, Iran is a part of Alpine-Himalayan belt. The consequences of most of the orogenic phases recorded in this tectonic belt. The Alpine orogeny, are traceable in Iran, and it can be said that the Alborz has a young and uninterrupted active tectonics, and now these activities continue [6]. From an engineering perspective, design engineers consider not only the slope stability but also the consequences in term of damage caused by slope failure. At the early stage, the majority of probabilistic studies aim to describe the slope stability using the probability of failure or a reliability index [7]. Slope stability analysis, especially for geotechnical engineers, is highly important because slope failure can have adverse social and economic impacts [8]. Different methods have been proposed for analyzing slope stability, including limit equilibrium method (LE), finite element method (FE) and finite difference method (FD).

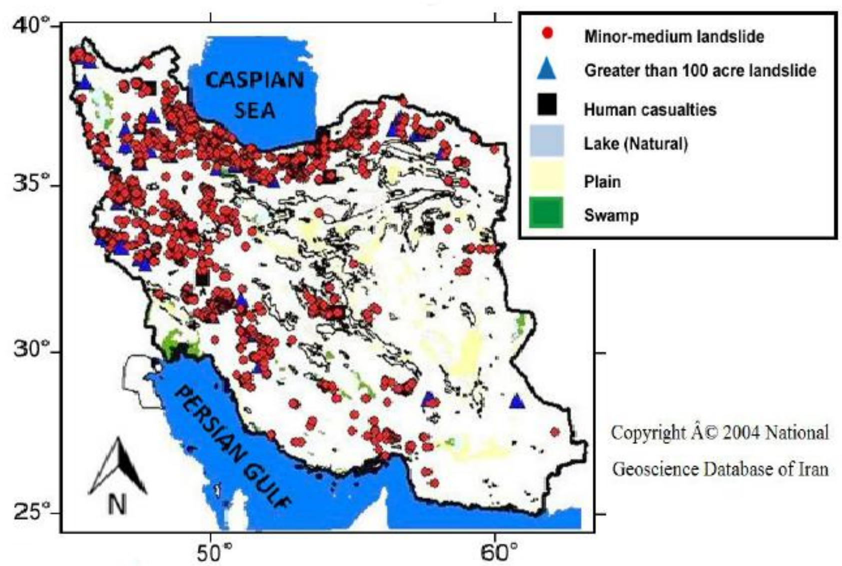

Fig. 1. The map of landslides scattering in Iran.

The method of limit equilibrium, which is one of the most commonly used methods of analysis, is based on considering one or more failure mechanisms and calculating the factor of safety against the failure mechanism. For several decades, the equilibrium method using the Mohr-Coulomb criterion has been the most common method for solving geotechnical engineering problems [9,10]. In limit equilibrium methods, the probability of slippage of rock or soil by gravity is investigated. The basis of all these methods is the comparison of resistance forces, moments, and stresses during mass motion relative to destructive forces, moments and tensions that create instability motion. In this way, based on known failure modes, the failure that leads to instability, is considered in the calculation. However, limit equilibrium methods are known as the simplest and most commonly used option, but if the slope failure mechanism is complicated (The existence of internal deformations, crispy failures, creep, liquefaction of weak soil layers and etc.), the use of these methods will not be suitable. In such a situation, advanced numerical modeling techniques should be used.

The most comprehensive analytical method used to study the behavior and response of slopes is numerical methods such as finite difference and finite element, which require accurate measurements of material properties and geotechnical parameters; so, a lot of time and money will be needed for these methods. Several studies have concluded that FE and FD methods have more advantages than the LE method. However, other studies have shown that the simplicity of the LE method is more important than the complexity of FE and FD methods [8]. And also in finite element methods, if we want to check the trend of stress-strain changes, the smaller mesh is needed that can reduce the computational speed, especially in more complicated models. Some studies suggest that in the case of increasing slope gradients; the finite element method results in less safety factor in comparison with a limit equilibrium approach. It is also observed that these differences will increase significantly with increasing groundwater level in the soil slope. In the presented study, it was attempted to evaluate the safety factor of a case study in Mazandaran province of Iran, and the landslide potential by PLAXIS finite element software compared to Geostudio- SLOPE/W software, which works based on the limit equilibrium method.

2. Materials and methods

2.1. Location of the studied slope

Zaremrood Basin is located in north of Iran and in the central part of Mazandaran province, 30 km south of Sari city. This basin is one of the most important sub-basins in the Tajan watershed (Fig. 2). This area has a massive forest cover, with moderate slopes. Most rainfall is rainy, but snow is seen locally in the winter months of the year. Based on Emberger method, the climate of the basin is very humid and the average rainfall is 998.5 mm. The Zaremrood basin, in terms of construction and geomorphology, has Jurassic ripplings that include a folded rippling series that has a simple structure which, the erosion process has not damaged them so much, but will gradually undergo erosion. Regular slopes, which are the largest facies in the basin, are located on the Marl unit with forest cover [11].

Fig. 2. Sertillite map of Barma Zarem Village (N 53°43'57.6 "E36o27'46.6").

This part of the eastern Alborz mountains in the southern part of the Paband National Park may know as the natural boundary of climate change, namely the semi-humid climates of the Caspian Sea and the semi-arid climate. The Zaremrood river crossing with a length of about 100 km, presence of Mount Zaram Kooh with a height of 2063 meters and its fountain which is the one sources of Zaremrood River are other characteristics of the village of Barma Zarem. Currently, the blockage of communication routes with the landslide in the mountainous and woodsy zones of this area is considered a serious threat, and the existence of 82 sliding points in Mazandaran province has raised concerns of the villagers.

Investigation of soil mass movements in this area shows that in this region, due to natural conditions including having fault structure, steep slope, wet climate, sensitive and non-resistant soil, has slip potential and human manipulation causes intensify mass movements. By comparison of landslides caused by human interference with ones caused by natural conditions, it appears that slopes with less humanly handworks, for the massive movements, generally need the gradient higher than 50%; this is where, the gradient is reduced to 20%, in the case of manipulated slopes. The results of soil texture testing in slip-over regions indicate that the soil texture of the region is composed of clayey loamy, sandy loamy and clayey sandy texture, and soil grading shows a fine-grained soil structure. These two points would validate the effect of susceptible soil factors in the occurrence of landslide phenomena. Most landslides have occurred on the slopes that covered by grass or where the trees has been cut off completely or where the road construction has cut off the continuity of the slopes and the passage of heavy machinery in this area has exacerbated mass movement around the road. Considering the increase in the number of residential complexes in recent years, the construction of these buildings on the sensitive soil and prone to slip has become a driving force to exacerbate this phenomenon. So, it can be claimed that one of the reasons of landslide occurrence in the studied area, is the weight of constructed buildings. In addition of these factors, the use of underground water sources in to develop the civil projects has brought down the groundwater level and by increasing the effective weight of the soil mass in susceptible areas, it has caused landslide movement [12].

2.2. Slope stability analysis with limit equilibrium method

In the analysis of slope stability using the limit equilibrium method, a failure mechanism is assumed and the slope stability is investigated by applying the equilibrium law and the behavioral equation on the fractured block. The limit equilibrium method is based on the ratio between the resistant and destructive forces. In this method, by determining the factor of safety, the slide or stability potential of the soil and rock masses in the slopes can be estimated.

Considering the resistance characteristics and geological features, in each area, it can be expected a unique slide. But the most important parameters affecting the models containing shear failure, are the angle of internal friction of the slope particles and the amount of the soil cohesion. There are generally two main forms of landslide failure: 1) Transitional slip in which a mass of material slides downward on an approximately rigid surface. 2) Circular or rotational slip that occurs along curved or spoon-shaped planes which sustains maximum shear stress [13]. Special geological conditions and tectonic breaks are usually not required to create a circular slip, while specific geological conditions, and in particular tectonic discontinuities with proper orientation, are among the factors causing a transitional slip. In this analysis, after determining the forces on the failure plane, the fracture tension calculates by equilibrium equations. In limit equilibrium methods, the probability of rock or soil sliding due to its gravity is investigated. Therefore, the balance of force or torque of the soil mass is examined on a probable failure plane. Soil above the failure plane is considered solid, so shear just may happen on this surface. Additionally, it is assumed that the shear strength of the soil on this plane is mobilized simultaneously. As a result, the safety factor of all points of the failure plane will be constant.

The main difference between the various limit equilibrium methods is in the assumptions about the shape of the sliding plane (circular, spiral, logarithmic, non-circular, and etc.) and also in the use of statics (use of total forces, total moments, and etc.) in the assessment of equilibrium and stability. In these types of models, after assigning of the soil properties and slope geometry, stability analysis is performed to ensure the forces that cause slope destruction are significantly less than the resistant forces.

In all limit equilibrium methods, it is presumed that the value of shear strength of probable fracture plane can be determined using linear or nonlinear Mohr-Coulomb equations.

The method of slices is the most popular technique among limit equilibrium methods. Stability analysis in this method involves passing the critical sliding plane from the soil mass and the surrounded section of the slope discretized into the vertical slices and finally determining the factor of safety [14,15]. In the ordinary method of slices, also called OMS or the Fellenius method, the sliding mass above the failure surface is divided into a number of slices. (Fig. 3).

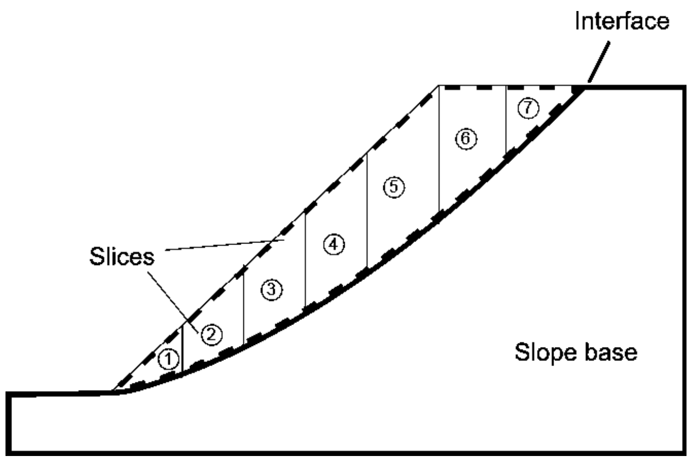

Fig. 3. Discretizing the slope in the method of slices.

The forces acting on each slice are obtained by considering the mechanical (force and moment) equilibrium for the slices. Each slice is considered on its own and interactions between slices are neglected because the resultant forces are parallel to the base of each slice. However, Newton's third law is not satisfied by this method because, in general, the resultants on the left and right of a slice do not have the same magnitude and are not collinear [16]. The force applied to a slice is generally shown as in Figure 4. In this figure it is assumed that the investigated block has the thickness of "b". The left and right slices apply the normal forces of E_l and E_r and the shear forces of S_l and S_r respectively. The weight of this slice produces a force equal to W, which is in equilibrium with pore pressure N and reaction T. It is supposed that each slice can rotate around a center and the moments around this center must also be in equilibrium.

The moment balance relationship of all slices is written as follows:

$$\sum M = 0 = \sum(W_j x_j - T_j r_j - N_j f_j - kW_j e_j) \quad (1)$$

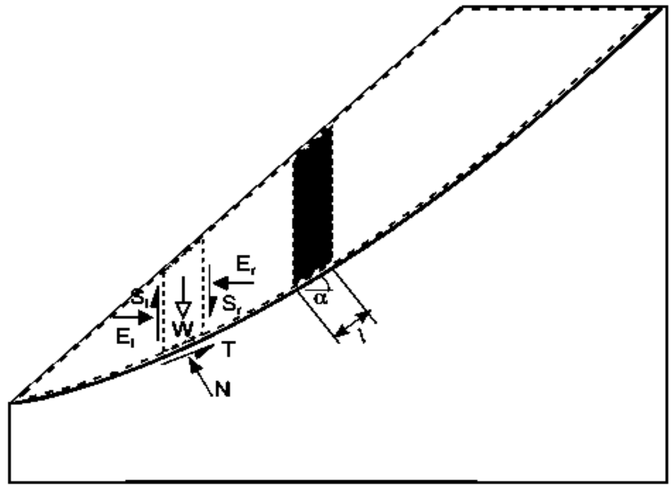

Fig. 4. Representation of force equilibrium vectors in the method slices.

Where "j" is the slice number and "x_j", "r_j", "f_j" and "e_j" are the moment arms. It can be stated by applying the theory of Terzaghi and converting stresses into the moment:

$$\sum \tau \, l_j \, r_j = l_j \, r_j \, \sigma' \tan \varphi' + l_j \, r_j \, c' \quad (2)$$

Therefore:

$$\sum \tau \, l_j \, r_j = r_j \, (N_j - u_j \, l_j) \tan\varphi' + l_j \, r_j \, c' \quad (3)$$

Where "u_j" is the pore water pressure. Eventually, the safety factor will be the ratio of the maximum moment to the estimated moment. The safety factor is one of the main outputs of limit equilibrium analysis. This coefficient is defined as the ratio of the shear strength of the slip surface to the applied shear stress and if the safety factor is less than "one", the slope will be unstable.

"SLOPE / W" is one of the software available in the "GeoStudio" series. The SLOPE/W is a two-dimensional software product that can be used to perform stress, and stability analyses of embankments. This software uses a variety of limit equilibrium methods for slope stability analysis and has been developed based on the safety factor equations for the equilibrium of moments and forces. It should be noted that all equilibrium methods use the Mohr-Coulomb constitutive model's equation and the assumption of the associated flow rule [17]. The SLOPE/W package for slope stability simulations in GeoStudio was used for modeling the slope stability. The input parameters used in modelling with SLOPE/W include the cohesion, friction angle, modulus of elasticity, Poisson’s ratio, hydraulic conductivity, bulk and dry unit weights and dilatancy angle.

2.3. Slope stability analysis with finite element method

Numerical modeling methods allow solving problems with complicated geometry, material anisotropy, nonlinear behavior, in-situ stress, and so on. Additionally, in numerical analysis, deformation and failure of the material, pore pressure, creep, dynamic loading, and material sensitivity to different parameters can also be evaluated. It should be noted that, numerical analysis methods have also some limitations. For example, achieving the needed information is often difficult and costly. On the other hand, these analyses should be carried out by expert and experienced users.

In the stress-strain method, the distribution of stress and strain in different parts of the slope are analyzed, and, the safety factor on the most probable fracture surface is determined. The most common way for the determination of F_s is to compare the maximum mobilized shear resistance on the interface with the total applied stresses on it. One of the ways of solving these equations is the use of the finite element method. In the finite element method, the stiffness matrix of components, which relates the force in each node to its displacement, is determined based on the minimizing of total potential energy. This method involves the transfer of the whole gravity of mass to a limited number of elements using the mesh created. Although it is stated that the finite element offers more advantages than the limit equilibrium, this method has some restrictions in the slope stability analysis [10,18], as follows:

- Providing variable results of the safety factor depending on the selected conditions.
- Lack of easiness in the interpretation of the results because it needs to be confirmed using go back to evidence and experience to check the accuracy of the model for predicting slope behavior.
- In the case of complex analyses, a well-trained user having modeling experience is necessitated because of the complexity of the method, the difficulty of conception and uncertainty in the results.
- Regularly measurement of input data is difficult and access to them is generally poor.

In some numerical methods, a strength reduction procedure (Phi-C reduction) is used to determine F_s. Using this process, some information can be obtained about the failure mechanism, the shear displacement pattern, stress contours and etc. The Phi-C reduction technique does not require to determine the position and shape (circular, linear and so on) of failure. This method was first used by Zienkiewics et al. [19], and since then, many researchers have used this method [18,20,21]. In this technique, the soil strength parameters such as the internal friction angle and cohesion are reduced so that the slope is on the verge of instability. Hence, the factor of safety Fs is defined as the ratio of the initial and final strength parameters. The main benefits of this method are as follows [22]:

A. The critical failure surface is automatically determined by the shear stress due to the applicated weight loads, and the strength reduction technique.
B. No assumptions are needed for the distribution of the interlayer shear force.
C. It is applicable in complex conditions and can provide information on stresses, displacements and pore pressures that are not obtainable in the equilibrium method.
D. It is possible to consider the effect of different constitutive equations and non-associated flow rule.

Plaxis 2D is a finite element package used for two-dimensional analysis of deformation and stability analysis in geotechnical engineering. It uses advanced soil constitutive models for the simulation of the non-linear, time-dependent and anisotropic behavior of soils and rocks. Plaxis 2D portfolio models the structure, the soil and the interaction between the structure and the soil. Soil layers parameters are inputted into Plaxis and the construction stages and boundary conditions are defined in an already defined geometry cross-section containing the embankment and soil layer model, then Plaxis automatically generates the unstructured 2D finite element meshes with options of global and local mesh refinements. Using its calculation facilities, Plaxis 2D undergoes a calculation process and presents the calculation and model outputs. Finally, it is noted that, in this study, the landslide was analyzed by a plane strain model.

2.4. Physical and geometrical characteristics of the model

The model created, simulates an earth slope in the Zaramrood, Mazandaran, Iran. The approximate dimensions of the studied slope were 460 meters in length and 145 meters in height. The slope consists of a layer of soil located on an inclined bedrock. Underground water is also flowed down of the slope, along with the bedrock. The geometry of the model created in the PLAXIS software is presented in Fig. 5, and the geomechanical parameters of soil above the bedrock are also summarized in Table 1.

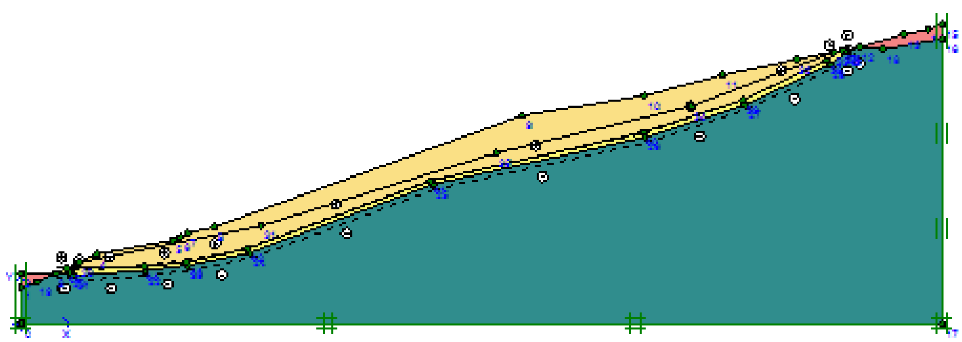

Fig. 5. Slope geometric and the materials layout

Table 1
Geomechanical characteristics of slope soil

Density (kN/m3)	Poisson Ratio	Elastic Modulus (kN/m2)	Cohesion (kN/m2)	Internal Friction Angle
20	0.35	10000	10	30

3. Results and discussion

Initial stresses in the model made with PLAXIS-2D software were performed using the gravity loading method. The initial stress contours that have been applied with this technique are represented in figure 6. The model is created with plane-strain assumptions. To use the Finite Element Method, a mesh containing 836 elements with an average size of 9.03 m was applied. The number of nodes and examined stress points was 7899 and 10032, respectively.

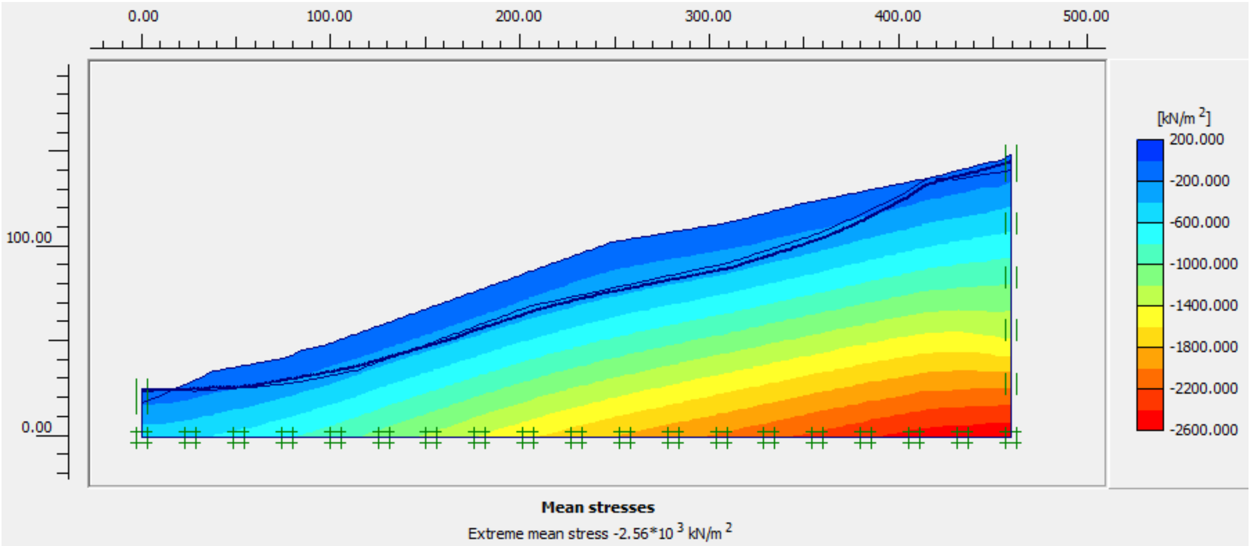

Fig. 6. The contour of initial stresses in the PLAXIS model using gravity loading method

3.1. The weakest wedge of the probable failure

By using Phi-C reduction method in finite element models, the sliding wedge, which has the highest chance of slipping, has always entered the plastic phase, and so the minimum value of Fs can be obtained; while the limit equilibrium method is highly dependent on surfaces that are presented by the user as a potential interface. In this case, the fracture wedge will be formed when the strength parameters of the soil are greatly reduced. As a result of this strength decrement the deformations of the simulated slope exit the elastic range due to the gravity or any other predefined forces, and enter the plastic phase.

The most probable failure wedge, in the case where the effect of the interface interaction between soil and bedrock ignored, is shown in Fig. 7. The factor of safety in this state is equal to 1.8035. The probable failure mechanism is shown in Fig. 8 using displacement vectors after the Phi-C reduction analysis method.

As explained, the resulted Fs from the SLOPE/W software and the corresponding collapsed wedge, strongly depend on the assumptions about the probable failure surface and the method utilized. If the simulated model contains the beginning and the ending points of the slope as the parts where the potential failure surface passes through, the resulting F_s will be related to the general slippage of the slope above the bedrock. In this case, smaller failures, will not be displayed, unlike the finite element method. Therefore, Grid and Radius method was used to find the fracture wedge, with the most probability, in SLOPE/W software. This technique can also coverage smaller arches having failure potential, on the slope. As illustrated in Fig. 9, the safety factor of this method is 1.858 and the specified probable failure surface has also a fit adaptation with PLAXIS software output. PLAXIS software has provided a lower safety factor, which is, although, a negligible difference. The minimum Fs obtained from the two methods were very close and, PLAXIS just resulted in safety factor about 3% lower than the F_s provided by SLOPE/W, which has been confirmed by other researchers [23].

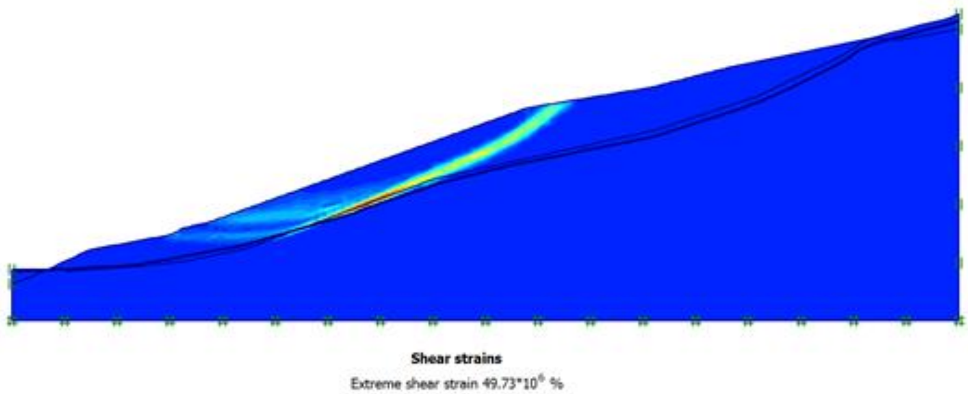

Fig. 7. Failure wedge display, after analysis by Phi-C reduction method.

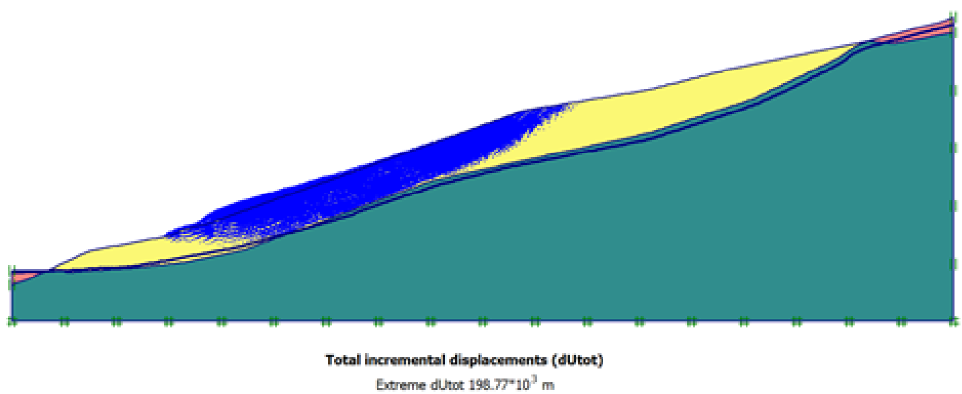

Fig. 8. Representation of the probable failure wedge using displacement vectors.

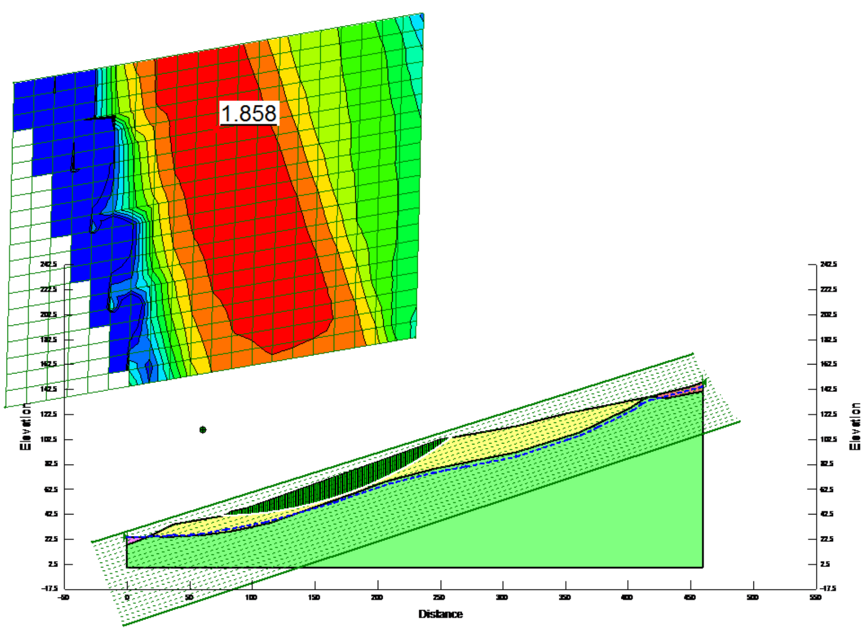

Fig. 9. Minimum safety factor of slope stability using Grid and Radius method.

3.2. Total landslide probability

As described, in order to determine the safety factor of general sliding in SLOPE/W, the surface of bedrock should be defined as the potential failure surface. In this case, landslide will occur exactly on the bedrock. But in PLAXIS software, to achieve this, changes in the soil resistance properties of the slope should be applied.

The factor of safety derived from modeling in PLAXIS software is corresponding to the weakest wedge and the surface with the most possibility of slippage. In this model, in order to obtain the safety factor of total slippage, soil strength parameters were manually increased, as a result, no local failure would occur in the slope, and a total slide occurs on the bedrock compulsorily. In parts of the model where more stresses are accumulated, there is a need for more elements and consequently smaller mesh [24]. As shown in Figure 10, the size of meshes on the bedrock, considered as the slide surface, is much smaller. Figure 11 shows the total slope wedge, which had achieved by Phi-C reduction method and resulted in a safety factor of 2.150. Also, in Fig. 12, the displacement contour due to the sliding on the bedrock has been shown.

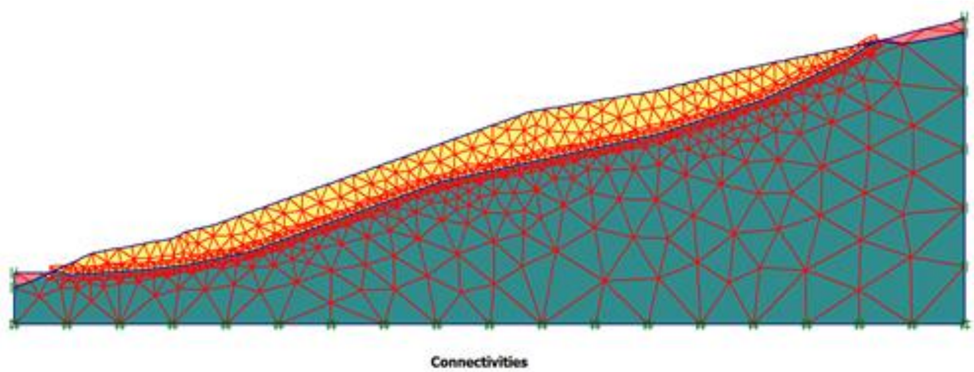

Fig. 10. Finite elements geometry and network with the interface element

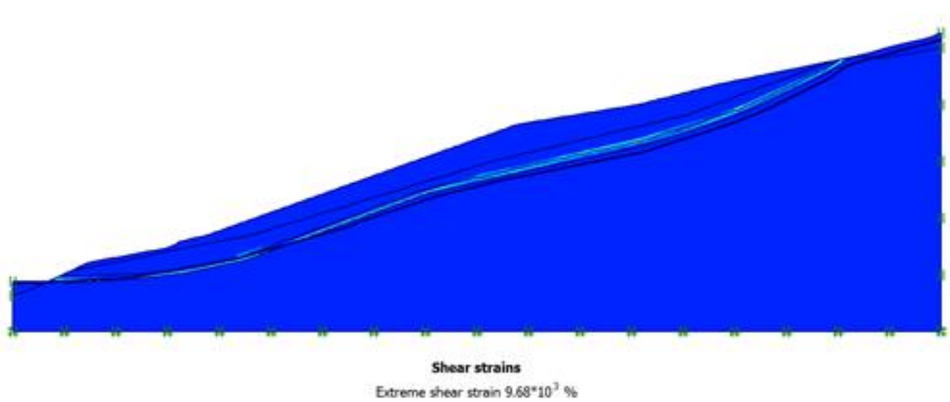

Fig. 11. Shear resistance contour of the slope to determine the sliding safety factor on bedrock

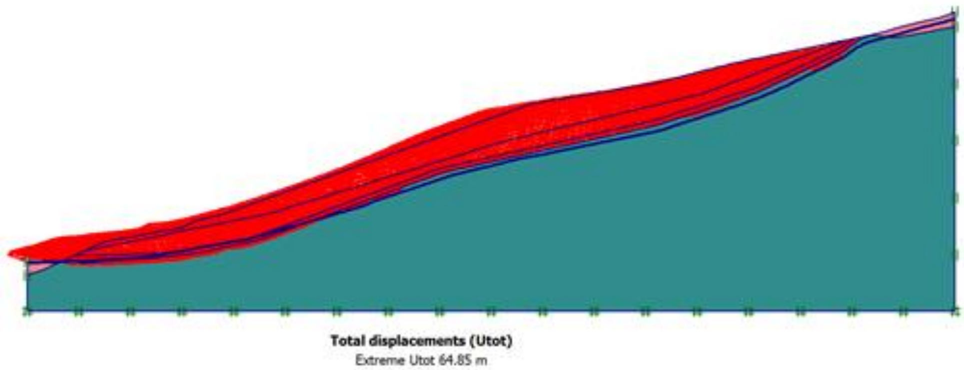

Fig. 12. Contour of displacements occurred during slippage on bedrock

The safety factor obtained by the limit equilibrium method used in the SLOPE/W software was 2.211. This value is close to the result of the PLAXIS software, but a little more than it. Figure 13 shows the shear resistance of all sliding points below the soil layer relative to the shear stress mobilized at these points. As can be seen, resistive values are about 2 times of shear stress that is mobilized in the bottom part of each slice, and this can be understood in the amount of safety factor.

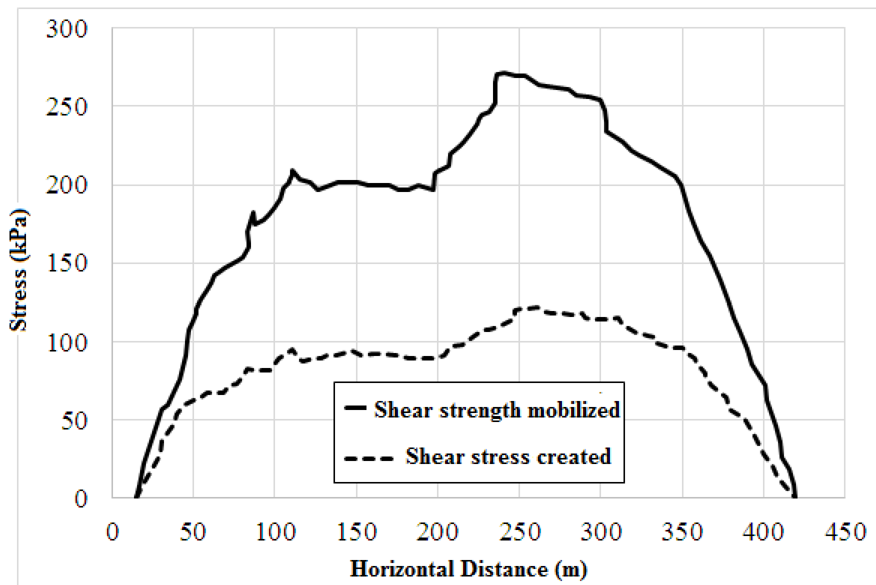

Fig. 13. Comparison of destructive shear stress mobilized and shear resistance on the total slippage plane.

4. Conclusion

In this study, a comparison was attempted between the results of software analysis of the slope stability by limit equilibrium and finite element methods. By appraising the probable fracture wedges provided by the software models, it was found that the results would be very close to each other if the model was properly formed. That is, by entering the correct values of the material properties and having a reasonable selection of the failure mode. By examining the process of the model simulation by this two software, and the output obtained, the following conclusion was drawn:

1. The authentic formation of the model, except its geometry, depends on certain factors which include entering appropriate values of the soil strength parameters according to the type of output required in the PLAXIS software, as well as precision in setting the expected surface to slide in the SLOPE / W software.
2. The F_s obtained by finite element method is about 3% lower than that obtained using the limit equilibrium method.
3. The localized failure zones in the PLAXIS model that entered the plastic phase, have a considerable proportionality with the probable wedge for the slip surface achieved by Radius & Grid technique used in the SLOPE/W software.
4. Most previous studies have shown a higher accuracy of the finite element method, but, considering the ease of use and less error possibility occurrence in the limit equilibrium method, it seems that this method utilization for solving problems with a simple geometry is reasonable.

References

[1] Cruden DM. A simple definition of a landslide. Bull Int Assoc Eng Geol 1991;43:27–9. doi:10.1007/BF02590167.

[2] Crozier M. Landslides: Causes, Consequences and Environment, Croom Helm Ltd, London or Sydney. ISBN 0-7099-0709-7. 1986.

[3] Turner A and RS. Landslides: Investigation and Mitigation: Transportation Research Board Special Report 247. National Research Council, Washington, DC, 1996. 673. n.d.

[4] A KP, S MA-Q, Chodani. Landslide hazard zonation in Iran. The landslide and a review of the landslides of Iran, ed. 1. Vol. 65. Iran: International Institute of Earthquake Engineering and Seismology 1994.

[5] The website of National Geosciences Database of Iran. [An Iranian governmental agency active in the field of geology]. Available from: www.ngdir.ir. n.d.

[6] Ghorbani M. Metallogenic and mining provinces, belts and zones of Iran, in The economic geology of Iran 2013:199–295.

[7] Cheng H, Chen J, Chen R, Chen G, Zhong Y. Risk assessment of slope failure considering the variability in soil properties. Comput Geotech 2018;103:61–72. doi:10.1016/j.compgeo.2018.07.006.

[8] Serra MP. Geotechnical stability analysis using student versions of FLAC, PLAXIS and SLOPE/W 2013.

[9] Duncan J, Wrigth S. Soil strength and slope stability, John Willey & Sons. Inc., Hoboken. New Jersey. 205AD.

[10] Hammouri NA, Malkawi AIH, Yamin MMA. Stability analysis of slopes using the finite element method and limiting equilibrium approach. Bull Eng Geol Environ 2008;67:471–8. doi:10.1007/s10064-008-0156-z.

[11] Roshun H. The Importance of Lithologic Units in Erosion and Sediment Studies (Case Study: Zarem Rood Watershed) 2011;8.

[12] Seyed Ata Ollah H, Elham Fazeli S, Majid L, Aidin P. Evaluating the effect of biological stabilization on landslide control at the edge of forest road. J For Sci 2017;63:496–502. doi:10.17221/99/2017-JFS.

[13] Cruden DM, Varnes DJ. Landslides: investigation and mitigation. Chapter 3-Landslide types and processes. Transp Res Board Spec Rep 1996.

[14] Abramson LW, Lee TS, Sharma S, Boyce GM. Slope stability and stabilization methods. John Wiley & Sons; 2001.

[15] Zhu DY, Lee CF, Jiang HD. Generalised framework of limit equilibrium methods for slope stability analysis. Géotechnique 2003;53:377–95. doi:10.1680/geot.2003.53.4.377.

[16] Fredlund DG, Krahn J. Comparison of slope stability methods of analysis. Can Geotech J 1977;14:429–39. doi:10.1139/t77-045.

[17] Duncan JM. State of the Art: Limit Equilibrium and Finite-Element Analysis of Slopes. J Geotech Eng 1996;122:577–96. doi:10.1061/(ASCE)0733-9410(1996)122:7(577).

[18] Griffiths D V., Lane PA. Slope stability analysis by finite elements. Géotechnique 1999;49:387–403. doi:10.1680/geot.1999.49.3.387.

[19] Zienkiewicz OC, Humpheson C, Lewis RW. Associated and non-associated visco-plasticity and plasticity in soil mechanics. Géotechnique 1975;25:671–89. doi:10.1680/geot.1975.25.4.671.

[20] Barla M, Barla G, Semeraro F, Aiassa S. Slope stability analysis of an Italian case study with the strength reduction method. 11th Int. Conf. Int. Assoc. Comput. Methods Ad-vances Geomech., vol. 19, 2005, p. 473–80.

[21] Matsui T, San K-C. Finite Element Slope Stability Analysis by Shear Strength Reduction Technique. Soils Found 1992;32:59–70. doi:10.3208/sandf1972.32.59.

[22] Griffiths D V., Fenton GA. Probabilistic Slope Stability Analysis by Finite Elements. J Geotech Geoenvironmental Eng 2004;130:507–18. doi:10.1061/(ASCE)1090-0241(2004)130:5(507).

[23] Khabbaz H, Fatahi B, Nucifora C. Finite element methods against limit equilibrium approaches for slope stability analysis. Aust. New Zeal. Conf. Geomech., Geomechanical Society and New Zealand Geotechnical Society; 2012.

[24] Ghiassian H, Jalili M, Kasemi D. Model study of sandy slopes under uniform seepage and reinforced with anchored geosynthetics. Geosynth Int 2009;16:452–67. doi:10.1680/gein.2009.16.6.452.